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An optical Fourier Transform spectrometer based on the Michelson interferometer with angle difference between two mirrors

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ABSTRACT

An optical spectrometer based on the Fourier transform is presented. Both the measured light and reference light are illuminated into a Michelson interferometer with angle difference between two mirrors, and the Fourier transform spectra of the interference fringes are obtained by using charge-coupled device (CCD) and the field-programmable gate array (FPGA). The peak point in the Fourier transform spectra of the reference light is used to calibrate the measured light, and the wavelength of the measured light can be detected by calculating the Fourier transform spectra between the measured light and the reference light. Due to the Michelson interferometer with angle difference between two mirrors, the Fourier transform spectrometer is realized without any mechanical movement, and the accuracy of the optical spectrometer is improved by propagating two lights into the common optical path in the same Michelson interferometer. The experiment shows that the maximum error is 1.15 nm. The proposed method possesses high performance, high reliability, and low cost.

1. Introduction

Optical spectrometer is increasingly essential in general chemical analysis, DNA sequencing, hazardous substances, and other applications in biology and chemistry [1–3]. Fourier transform spectrometer (FTS) has attracted a great deal of attention over the past decade because of their particular characteristics, such as high accuracy, high sensitivity, and high spectral resolution [4,5].

In the conventional FTS, the intensity of the output beam is measured by scanning an interferometer, and the optical path difference (OPD) of the interferometer determines the resolution of the FTS [6]. Recently, some different forms of FTS have been researched [7–9]. A FTS is presented by using a laser source of the pet watt-power ultra short pulse, which could measure the property of the chemical compounds precisely [10]. Moreover, a scan-less FTS based on an optical fiber interferometer is demonstrated, which possesses high resolution and low cost [11]. Besides, a birefringent prism is utilized in the FTS with a pair of polarizer and a linear CCD array [12–14]. This design improves the conventional FTS by eliminating movable parts and spreading the optical path difference (OPD) spatially, making the system smaller, more reliable, and greatly reducing measurement time. However, these methods always require complex components, which are unsuitable in real engineering.

In this paper, an optical spectrometer based on the Fourier transform is presented. Both the measured light and reference light are illuminated into a Michelson interferometer, and the Fourier transform spectra of the interference fringes are obtained by using charge-coupled device (CCD) and the field-programmable gate array (FPGA) [15–17]. The peak point in the optical spectrum of the reference light is used to calibrate the measured light, and the spectrum of the measured light can be detected by calculating the Fourier transform spectra between the measured light and the reference light. Due to the Michelson interferometer with angle difference between two mirrors, the Fourier transform spectrometer is realized without any mechanical movement, and the accuracy of the optical spectrometer is improved by propagating two beams of light into the common optical path in the same Michelson interferometer. The proposed method possesses high performance, high reliability, and low cost.

2. The experimental setup of the spectrometer

The experimental setup of the spectrometer is shown in Fig. 1. The reference light is a solid laser with the wavelength of 531.5 nm and output power of 2 mW. A Michelson interferometer

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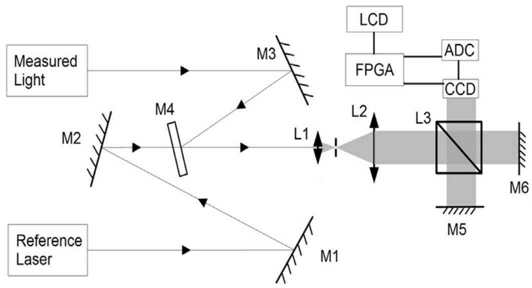

Fig. 1. The experimental setup of the Fourier transform optical spectrometer.

is constructed by using two mirrors (M5 and M6) and a polarizing beam splitter L3. Both the measured light and reference light are propagated into the collimated lens L1 and L2 after three reflectors (M1, M2 and M3) and a half mirror M4, and illuminated into the Michelson interferometer with the common optical path. Then interference fringes of the measured light and the reference light are converted into electronic signal by using the linear CCD and the Fourier transform spectra of interference fringes are calculated by using FPGA.

3. Principle of the measurement

The optical path of the Michelson interferometer is showed in Fig. 2. The distance between the M5 and L3 is the same as that between M6 and L3. The M6 is rotated with a small angle compared to the M5. Therefore, the OPD of Michelson interferometer is produced by the angle difference between M5 and M6.

Assuming that θ is the angle difference between the M5 and M6, point O is the cross point between two mirrors, and point O' is the corresponding point of O in the CCD. The OPD can be expressed as

$$d = 2x \tan\theta \tag{1}$$

where d is the OPD, x is the absolute distance between the pixel point and the point O' in CCD.

Therefore, the interference fringes of the measured light and the reference light can be expressed as

$$I_m = I_{b1} + I_{c1} \cos\left(\frac{2\pi}{\lambda_m} d\right) \tag{2}$$

$$I_r = I_{b2} + I_{c2} \cos\left(\frac{2\pi}{\lambda_r} d\right) \tag{3}$$

where I_m and I_r are the intensity of the measured light and the reference light, I_{b1} and I_{b2} are the background light, I_{c1} and I_{c2} are the contrast light, λ_m and λ_r are wavelengths of the measured light and the reference light.

Then the interference fringes of the measured light and the reference light are converted into electronic signal by using the linear CCD and the Fourier transform spectra of interference fringes are

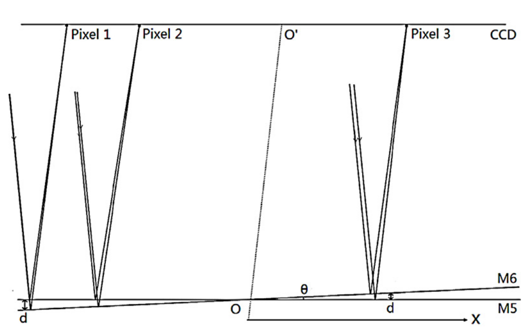

Fig. 2. The diagram of interference between M5 and M6.

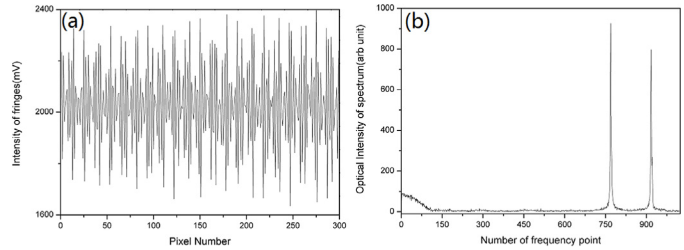

Fig. 3. (a) The interference fringes of reference light and the measured light. (b) Fourier transform spectrum of the interference fringes.

calculated by using FPGA. The Fourier transform spectra of the interference fringes, G_m and G_r, can be given by

$$G_m(f) = A_{b1} + B_{c1}(f + f_m) + B^*_{c1}(f - f_m) \tag{4}$$

$$G_r(f) = A_{b2} + B_{c2}(f + f_r) + B^*_{c2}(f - f_r) \tag{5}$$

where A_{b1} and A_{b2} are the Fourier transform of the background light, B_{c1} and B_{c2} are the Fourier transform of the contrast light, * denotes a complex conjugate, f_m and f_r are the main frequency of interference fringes, which are given by

$$f_m = \frac{2\tan\theta}{\lambda_m} \tag{6}$$

$$f_r = \frac{2\tan\theta}{\lambda_r} \tag{7}$$

Therefore, the wavelength of the measured light can be calculated by comparing the main frequencies of Fourier-transforming interference fringes between the measured light and the reference light, which is given by

$$\lambda_m = \lambda_r \frac{f_r}{f_m} \tag{8}$$

4. Experiment and discussion

The performance of the optical spectrometer is investigated by applying a solid laser as reference light with the wavelength of 531.5 nm and a measured light with the wavelength of 632.8 nm. The angle θ is 1.90°. The interference fringes of reference light and the measured light were converted into electronic signal by using the linear CCD, as shown in Fig. 3(a). Due to the different wavelengths of the reference light and the measured light, the profile of the interference fringe is modulated.

Then Fourier transform spectrum of the interference fringe was calculated, as shown in Fig. 3(b). The x-coordinate is the frequency point and it also represents the frequency. Given that the frequency points of peaks corresponding to reference light and measured light are N_r and N_m, respectively. According to Eqs. (6) and (7), the relationship between the frequency point and main frequency and wavelength is given by

$$N_m = f_m \times \frac{N}{F_s} = \frac{2N\tan\theta}{\lambda_m F_s} \tag{9}$$

$$N_r = f_r \times \frac{N}{F_s} = \frac{2N\tan\theta}{\lambda_r F_s} \tag{10}$$

where N is half of the sampled datum amount and F_s is the sampling frequency. Substituting Eq. (10) into Eq. (9) provides

$$\frac{N_r}{N_m} = \frac{f_r}{f_m} = \frac{\lambda_m}{\lambda_r} \tag{11}$$